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CONTROLLED AND UNCONTROLLED DISORDER IN OPTICAL LATTICE EMULATORS

Vito Scarola
VIRGINIA POLYTECHNIC INST AND STATE UNIVERSITY

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Final Report

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14. ABSTRACT
Our work studies novel phases of matter potentially realizable with ultracold atomic gases confined in optical lattices and models the impact of controlled and uncontrolled disorder on these optical lattice phases. Atoms (either bosons or fermions) placed in optical lattices can interact to form strongly correlated states. Our work seeks to foster experimental work with these states, which include, superfluids, superconductors, supersolids, glasses, topological states, and other quantum many-body states because they are of fundamental importance in understanding the collective behavior of quantum particles. These states are potentially impacted by spatial and phase fluctuations, trapping, laser noise, and other sources of uncontrolled disorder. Controlled disorder can also be used to drive the system into interesting new regimes as well.
This award has led to significant accomplishments over the past three years that pertain directly to the goals of the grant: 22 publications and manuscripts (5 in Physical Review Letters), 13 students and postdocs mentored, 27 invited presentations given. The award has also allowed us to establish direct connections with experimental groups (via travel and shared projects).

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Final Report: Controlled and Uncontrolled Disorder in Optical Lattice Emulators

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Program Manager: Tatjana Curcic

PIs: Vito Scarola (Virginia Tech, scarola@vt.edu)

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I. Summary of Research Highlights

Our work studies novel phases of matter potentially realizable with ultracold atomic gases confined in optical lattices and models the impact of controlled and uncontrolled disorder on these optical lattice phases. Atoms (either bosons or fermions) placed in optical lattices can interact to form strongly correlated states. Our work seeks to foster experimental work with these states, which include, superfluids, superconductors, supersolids, glasses, topological states, and other quantum many-body states because they are of fundamental importance in understanding the collective behavior of quantum particles. These states are potentially impacted by spatial and phase fluctuations, trapping, laser noise, and other sources of uncontrolled disorder. Controlled disorder can also be used to drive the system into interesting new regimes as well.

This award has led to significant accomplishments over the past three years that pertain directly to the goals of the grant:

- 22 publications and manuscripts (5 in Physical Review Letters)
- 13 students and postdocs mentored
- 27 invited presentations given

The award has also allowed us to establish direct connections with experimental groups (via travel and shared projects). These groups include Peter Engel's group at Washington State University, Ian Spielman's group at NIST/JQI/UMD, and Brian DeMarco's group at the University of Illinois at Urbana-Champaign.

Our work established and analyzed models that guide the ultracold atom community in realizing novel states of matter with optical lattices. Our work discovered new classes of many-body models that meet goals of the proposal 1) Our models of controlled disorder show that it can be an asset to revealing many-body states 2) Strong interactions can often stabilize intriguing states of matter against fluctuations (particularly, thermal fluctuations). 3) Topological quantum phases are robust against quantum and thermal fluctuations. The following briefly summarizes some of our major research accomplishments. Section V expands on this summary as well.

- The Bose glass is an intriguing disordered state of bosons defined by local order. To-date it has not been observed experimentally. We proposed a local measure, boson core compressibility, which uses double occupancy for identification of a Bose-Glass and other states (Publication 18).
- A supersolid, a simultaneous superfluid and solid, might be made possible via dipolar interactions between bosons in optical lattices. It has not been observed to date. Supersolids are believed to be rather delicate, but we discovered that controlled disorder *enhances* the strength of supersolids (Publication 19).
- Topological states of matter can reveal intriguing excitations, Majorana fermions, that interact non-locally to demonstrate anyon braid statistics. Unfortunately, their non-local character is not observable at non-zero temperature in 1D. We constructed

a model capturing the essential properties of dipolar fermions in optical lattices. We found that strong anisotropic interactions suppress unwanted phase disorder (fluctuations) in 2D to pave the way for observing these interesting excitations (Publication 13).

- Flat bands possess macroscopic level degeneracy and play a crucial role in many important physical phenomena. However, most previous lattice models for generating flat bands involve either high orbital bands or high order tunnelings, which are generally very challenging in experiments. We showed that the combination of spin-orbit coupling, Zeeman field and optical lattice potential can yield isolated flat ground state bands where topological properties may originate from the spin-orbit coupling (Publication 14).
- Intriguing many-body states are possible with spin-orbit coupling but implemented schemes for generating the necessary fields lead to unwanted heating and losses near Feshbach resonances, precisely the many-body regime of interest. We found that heating and losses can be avoided in flat bands while still revealing interesting fractionalized many-body states (Publication 7).
- We studied, for the first time, the BCS-BEC crossover in a spin-orbit coupled degenerate Fermi gas. We showed that topological excitations, such as the long-sought Weyl and Majorana fermions, can exist in such systems. We found various disorders, including the low dimensional phase disorders (fluctuations), do not destroy such topological states (Publication 17, 20, 22).
- We demonstrated the existence of a new route for realizing the long sought FFLO superfluids using spin-orbit coupled degenerate Fermi gases. Such FFLO superfluids can support topological excitations such as Majorana fermions in certain parameter regimes. We further showed such FFLO phases are much more stable than the traditional population imbalanced induced FFLO phases in low dimension (already studied extensively in experiments), where the finite temperature induced phase disorder (fluctuations) are crucial (Publication 5, 9, 12).
- In Collaboration with Peter Engels experimental group, we observed, for the first time, the long-sought Zitterbewegung phenomenon, the simultaneous velocity (thus position) and spin oscillations, for neutral atoms using spin-orbit-coupled Bose-Einstein condensate (BEC) through sudden quantum quenches of the system Hamiltonian. Together we also observed a moving antiferromagnetic order using a phase-winding BEC. Antiferromagnetic order has been extensively studied in optical lattices (one major goal for the DARPA optical lattice emulator program), and only recently some signatures were observed in optical lattice experiments (Hulet group) (Publication 10, 11)

II. List of Supervised Students and Postdoctoral Researchers:

Peter Raum (Virginia Tech Graduate Student)

Mi Yan (Virginia Tech Graduate Student)

Yanfei Tang (Virginia Tech Graduate Student)

Mengsu Chen (Virginia Tech Graduate Student)

Yasamin Khorramzadeh (Virginia Tech Graduate Student)

Bhargav Kemburi (Virginia Tech Undergraduate Student)

Fei Lin (Virginia Tech Postdoc)

Yongping Zhang (WSU Postdoc)

Yinyin Qian (UTDallas Graduate Student)

Chunlei Qu (UTDallas Graduate Student)

Ming Gong (UTDallas Postdoc)

Yong Xu (UTDallas Postdoc)

Zhen Zheng (UTDallas Visiting Graduate Student)

III. List of Publications and Preprints Supported by This Project:

(Underlined authors are from PIs' groups)

5 Phys. Rev. Lett. 1 Europhys. Lett., 5 preprints, 10 Phys. Rev. A and B

1. The Phase diagram of the ν=5/2 fractional quantum Hall effect: effects of Landau level mixing and non-zero width, K. Pakrouski, M. R. Peterson, T. Jolicoeur, **V. W. Scarola**, C. Nayak, M. Troyer , Submitted to Phys. Rev. X Preprint (2014). arXiv:1411.1068
2. Floquet FFLO superfluids and Majorana fermions in a shaken fermionic optical lattice, Z. Zheng, C. Qu, X. Zou, and **C. Zhang**, manuscript in preparation.
3. Disorder and the phase diagram of the extended Bose-Hubbard model, F. Lin and **V. W. Scarola**, manuscript in preparation.
4. Uniaxial charge density wave of fractional charges in a fractional Chern insulator model, M. Chen and **V. W. Scarola**,. Submitted to Phys. Rev. Lett. Preprint (2014). arXiv:1409.5372
5. Berezinskii-Kosterlitz-Thouless phase transition in 2D spin-orbit coupled FF superfluids, Y. Xu, **C. Zhang**, Preprint (2014). arXiv:1407.3483
6. Spin-Orbit driven transitions between Mott insulators and finite momentum superfluids of bosons in optical lattices, Y. Qian, M. Gong, **V. W. Scarola**, and **C. Zhang**, Preprint (2013). arXiv:1312.4011
7. Emergent kinetics and fractionally charged excitations in 1D spin-orbit coupled flat Band Optical Lattices, F. Lin, **C. Zhang**, and **V. W. Scarola**, Phys. Rev. Lett. 112, 110404 (2014). arxiv:1308.5601
8. Néel temperature and thermodynamics of the half-filled 3D Hubbard model by Diagrammatic Determinant Monte Carlo, E. Kozik, E. Burovski, **V.W. Scarola**, and M. Troyer, Phys. Rev. B 87, 205102 (2013). arxiv:1212.3027
9. Competing superfluid orders in spin-orbit coupled fermionic cold atom optical lattices, Y. Xu, C. Qu, M. Gong, **C. Zhang**, Phys. Rev. A 89, 013607 (2014). arXiv:1305.2152
10. Phase winding a two-component BEC in an elongated trap: experimental observation of moving magnetic orders and dark-bright solitons, C. Hamner*, Y. Zhang*, J. J. Chang*, **C. Zhang**, P. Engels, Phys. Rev. Lett. 111, 264101 (2013), arXiv:1306.6102
*Contributed equally to this work
11. Observation of Zitterbewegung in a spin-orbit-coupled Bose-Einstein condensate, C. Qu, C. Hamner, M. Gong, **C. Zhang**, P. Engels, Phys. Rev. A, 88, 021604(R) (2013). arxiv:1301.0658
12. Route to observable Fulde-Ferrell-Larkin-Ovchinnikov phases in 3D spin-Orbit coupled degenerate Fermi gases, Z. Zheng, M. Gong, X. Zhou, **C. Zhang**, and G.-C. Guo, Phys. Rev. A **87**, 031602(R) (2013). arxiv:1208:2029
13. Enhancing the thermal stability of entanglement between Majorana fermions with dipoles in optical lattices, F. Lin and **V.W. Scarola** Phys. Rev. Lett. 111, 220401 (2013). arxiv:1210.0799
14. Bose-Einstein condensates in Spin-Orbit coupled optical lattices: flat bands and superfluidity, Y. Zhang, and **C. Zhang** Phys. Rev. A 87, 023611 (2013). arxiv:1203.2389

15. Exotic superfluidity in spin-orbit coupled Bose-Einstein condensates, Q. Zhu, **C. Zhang**, B. Wu, Europhysics Letters 100, 50003 (2012). arxiv:1109.5811
16. Dzyaloshinskii-Moriya interaction and spiral order in spin-orbit coupled optical lattices, M. Gong, Y. Qian, **V. W. Scarola**, and **C. Zhang** *Preprint* (2012). arxiv:1205.6211
17. Searching for Majorana fermions in 2D spin-orbit coupled Fermi superfluids at finite temperature, M. Gong, G. Chen, S. Jia, **C. Zhang**, Phys. Rev. Lett. 109, 105302 (2012). arxiv:1201.2238
18. Boson core compressibility, Y. Khorramzadeh, Fei Lin, and **V. W. Scarola** Phys. Rev. A 85*, 043610* (2012). arxiv:1201.0523
19. Percolation enhanced supersolids in the extended Bose-Hubbard model, B.M. Kemburi and **V. W. Scarola**, *Phys. Rev. B*. 85, 020501 (2012). arxiv:1110.2957
20. BCS-BEC crossover in spin-orbit coupled two-dimensional Fermi gases, G. Chen, M. Gong, and **C. Zhang**, Phys. Rev. A 85, 013601 (2012). arXiv:1107.2627
21. Thermal versus quantum fluctuations of optical lattice fermions , V. L. Campo, K. Capelle, C. Hooley, J. Quintanilla, and **V. W. Scarola**, Phys. Rev. A 85, 033644 (2012). arXiv:1107.4349
22. BCS-BEC crossover and topological phase transition in 3D spin-orbit coupled degenerate Fermi gases, M. Gong, S. Tewari, and **C. Zhang**, Phys. Rev. Lett**.** 107, 195303 (2011). arXiv:1105.1796

IV. List of Presentations Given Related to This Project

Invited Presentations by PI Scarola:

1. *Engineering Strongly Correlated States with Ultracold Atoms* Invited Conference Talk: Inaugural Mid-Atlantic Section Meeting of the APS, Penn State-State College, Pennsylvania October 2014.
2. *Stability of Quantum Matter and Extreme Spin-orbit Coupling* Invited Conference Talk: ARO MURI Program Review Joint Quantum Institue/University of Maryland–College Park, Maryland, October 2014.
3. *New Directions for Engineering Quantum Spin States: Ultracold Atomic Gases with Optically Induced Synthetic Spin-Orbit Coupling* Invited Conference Talk: San Diego SPIE Spintronics and Optics Symposium, August 2014.
4. *Quantum State Engineering with Ultracold Atoms* Invited Seminar: SUNY Buffalo-Buffalo, New York, March 2014
5. *Vortex Attachment in Spin-Orbit Coupled Systems* ARO MURI Program Review, JQI/University of Maryland, College Park Maryland, December 2013.
6. *Topological Matter* Invited Seminar: Purdue University–West Lafayette, Indiana, August 2013.
7. *Vortex Attachment in Spin-Orbit Coupled Systems* DARPA Optical Lattice Emulator Review, San Francisco, California, May 2013.
8. *Quantum Emulation with Cold Atom Optical Lattices* Invited Seminar: Oakridge National Laboratory–Oak Ridge, Tennessee, May 2013.
9. *Thermal Stability of Majorana Fermions* Invited Conference Talk: ARO MURI Program Review Joint Quantum Institue/University of Maryland–College Park, Maryland, October 2012.
10. *Quantum Emulation with Cold Atom Optical Lattices* DARPA Optical Lattice Emulator Review, Chicago, Illinois May 2012.
11. *Quantum Emulation with Cold Atom Optical Lattices* Invited Colloquium: William and Mary–Williamsburg, Virginia April 2012.
12. *Quantum Emulation with Cold Atom Optical Lattices,* Invited Colloquium: AFOSR AMO Program Review, Arlington, Virginia January 2012.
13. *Quantum Emulation with Cold Atom Optical Lattices,* Invited Colloquium: Washington State University–Pullman, Washington, January 2012.
14. *Supersolids in the Disordered Extended Bose-Hubbard Model* DARPA Optical Lattice Emulator Review, Fort Lauderdale, Florida, December 2011.
15. *Flat-band Lattices and Fractional Quantum Hall States*, Invited Conference Talk: 78th Annual Meeting of the Southeastern Section of the APS, Roanoke, Virginia, October 2011.
16. *Flat-band Lattices and Fractional Quantum Hall States,* Invited Seminar: University of Maryland–College Park, Maryland, September 2011.

Invited Presentations by PI Zhang:

1. *Topological Superfluids with Finite Momentum Pairing in Spin-Orbit Coupled Fermi Gases*, OCPA conference, Singapore, June 2014
2. *Search for Majorana fermions in spin-orbit coupled superconductors and superfluids*, Condensed Matter Seminar, Department of Physics and Astronomy, University of Pittsburgh, April 2014, Pittsburgh, PA
3. *Search for Majorana fermions in spin-orbit coupled superconductors and superfluids*, Physics Colloquium, Department of Physics, Oklahoma State University, April 2014, Stillwater, OK
4. *Search for Majorana fermions in spin-orbit coupled degenerate Fermi gases*, American Physical Society March Meeting invited talk, March 2013, Baltimore, Maryland.
5. *Search for Majorana fermions in spin-orbit coupled superconductors and superfluids*, Condensed Matter seminar, Department of Physics, Purdue University, March 2013, West Lafayette, IN.
6. *Search for Majorana fermions in spin-orbit coupled superconductors and superfluids*, Physics Colloquium, Department of Physics, University of Washington, October 2012, Seattle, Washington.
7. *Ultra-cold atoms in spin-orbit coupled optical lattices*, ARO "Atomtronics" MURI program review meeting, University of Maryland, October 2012, College Park, Maryland
8. *Topological Superfluids in Spin-Orbit Coupled Cold Fermi Gases: a Roadmap to Majorana Fermions*, AMO Seminar, Department of Physics, Rice University September 2012, Houston, Texas
9. *Spin-Orbit Coupled Degenerate Fermi Gases: A Platform for Majorana Fermions*, DARPA Optical Lattice Emulator program meeting, May 2012, Chicago, IL
10. *Topological Superfluids in Spin-Orbit Coupled Cold Fermi Gases: a Roadmap to Majorana Fermions*, Physics Colloquium, Temple University, March 2012, Philadelphia, PA
11. *Topological Quantum Materials at Nanoscale: a Roadmap to Majorana Fermions,* Physics Colloquium, The University of Texas at Dallas, February 2012, Richardson, TX
12. *Tunable Spin-orbit Coupling and Quantum Phase Transition in a Trapped Bose-Einstein Condensate*, DARPA Optical Lattice Emulator program meeting, December 2011, Fort Lauderdale, Florida.
13. *Spin-Orbit Coupled Bose-Einstein Condensates and Degenerate Fermi Gases*, Physics Colloquium, Department of Physics, Indiana University Purdue University Indianapolis, October 2011, Indianapolis, Indiana

V. Selected Project Highlights

Emergent Kinetics and Fractionally Charged Excitations in 1D Spin-Orbit Coupled Flat Band Optical Lattices,

F. Lin, **C. Zhang**, and **V. W. Scarola**

Phys. Rev. Lett. 112, 110404 (2013) arXiv:1308.5601

Recent ultracold atomic gas experiments implementing synthetic spin-orbit coupling allow access to flat bands that emphasize interactions. In our work we modeled spin-orbit coupled fermions in a one-dimensional flat band optical lattice. We introduced an effective Luttinger liquid theory to show that interactions generate collective excitations with emergent kinetics and fractional charge, analogous to emergence of Fermi-liquid properties in the fractional quantum Hall regime. Observation of these excitations would provide an important platform for exploring exotic quantum states derived solely from interactions.

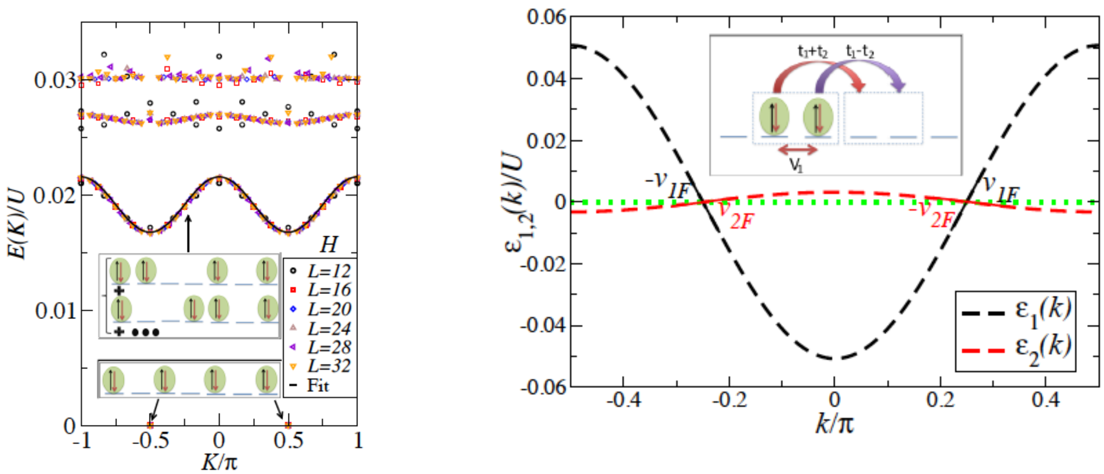


Figure Caption: (Left) Symbols denote the man-body energy dispersion computed for the Hubbard interaction in a flat spin-orbit band. The schematics denote a real space depiction of a Wigner crystal ground state with dispersive collective modes. (Right) Emergent single-particle energy dispersion versus wavevector. The inset depicts the emergent hopping that derives purely from interactions.

Néel temperature and thermodynamics of the half-filled 3D Hubbard model by Diagrammatic Determinant Monte Carlo,
E. Kozik, E. Burovski, **V.W. Scarola**, M. Troyer

Phys. Rev. B **87**, *205102 (2013)*. arXiv: 1212.3027

Ultracold atomic gases experiments seeking to emulate the Fermi Hubbard model are currently attempting to reach temperatures low enough to realize spin ordering. In this work we studied the thermodynamics of the 3D Hubbard model at half filling on approach to the Néel transition by means of large-scale unbiased Diagrammatic Determinant Monte Carlo simulations. We obtain the transition temperature in the strongly correlated regime, as well as temperature dependence of energy, entropy, double occupancy, and the nearest-neighbor spin correlation function. Our results improve the accuracy of previous unbiased studies and present accurate benchmarks in the ongoing effort to realize the antiferromagnetic state of matter with ultracold atoms in optical lattices.

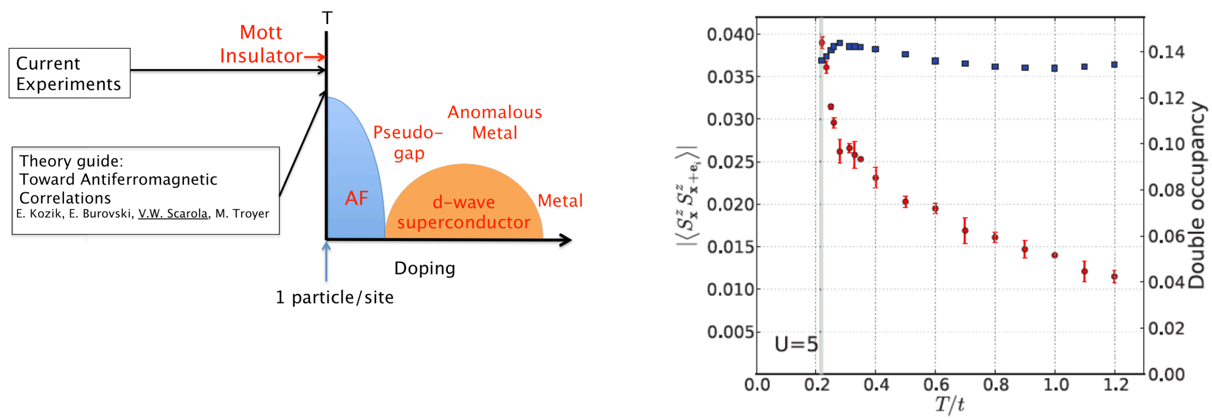


Figure Caption: (Left) Schematic phase diagram showing several phases of high temperature superconductors. Arrows indicating current experiments and our theory work show the operating temperatures of optical lattice experiments emulating the Hubbard model and our calculations, respectively. (Right) Nearest neighbor spin correlation functions and the double occupancy plotted as a function of temperature as the Neel state is approached on the left and right axes, respectively.

Observation of Zitterbewegung in a spin-orbit-coupled Bose-Einstein condensate

C. Qu, C. Hamner, M. Gong, **C. Zhang**, P. Engels

Phys. Rev. A, 88, 021604(R) (2013). (**49 citations**)

Spin-orbit-coupled ultracold atoms provide an intriguing new avenue for the study of rich spin dynamics in superfluids. In this work, we observed Zitterbewegung, the simultaneous velocity (thus position) and spin oscillations, of neutral atoms between two spin-orbit-coupled bands in a Bose-Einstein condensate (BEC) through sudden quantum quenches of the Hamiltonian. The observed Zitterbewegung oscillations are perfect on a short time scale but gradually damp out on a long time scale, followed by sudden and strong heating of the BEC. As an application, we also demonstrated how Zitterbewegung oscillations can be exploited to populate the upper spin-orbit band and observe a subsequent dipole motion. Our experimental results were corroborated by a theoretical and numerical analysis and showcased the great flexibility that ultracold atoms provide for investigating rich spin dynamics in superfluids.

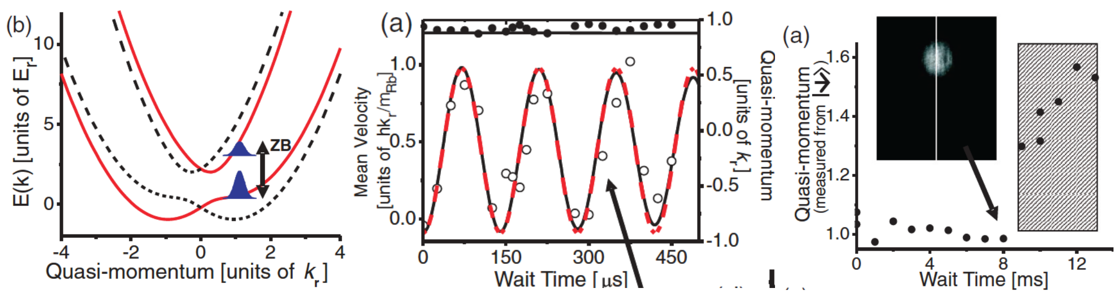


Figure Caption: (Left) Spin-orbit coupled band structure. The sudden change of the detuning of two spins induces the coupling between two bands, leading to Zitterbewegung oscillations. (Middle) The experimental observed short time ZB oscillation. The velocity of atoms oscillates with time. (Right) Decay of the ZB oscillation in a long time scale due to many-body interaction between atoms.

Route to Observable Fulde-Ferrell-Larkin-Ovchinnikov Phases in 3D Spin-Orbit Coupled Degenerate Fermi Gases,

Z. Zheng, M. Gong, X. Zhou, **C. Zhang**, and G.-C. Guo,

Phys. Rev. A **87**, 031602(R) (2013). arXiv:1208:2029 (**37 citations**)

The Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase was first predicted in two-dimensional superconductors about 50 years ago, but so far unambiguous experimental evidence is still lacking. The recently experimentally realized spin-imbalanced Fermi gases may potentially unveil this elusive state, but they require very stringent experimental conditions. In this work, we showed that FFLO phases may be observed even in a three-dimensional (3D) degenerate Fermi gas with spin-orbit coupling and an in-plane Zeeman field. The FFLO phase is driven by the interplay between the asymmetry of the Fermi surface and the superfluid order, instead of the interplay between magnetic and superconducting order in solid materials. The predicted FFLO phase exists in a giant parameter region, possesses a stable long-range superfluid order due to the 3D geometry, and can be observed with an experimentally already achieved temperature (T ~ 0.05EF), thus opening a fascinating avenue for exploring FFLO physics.

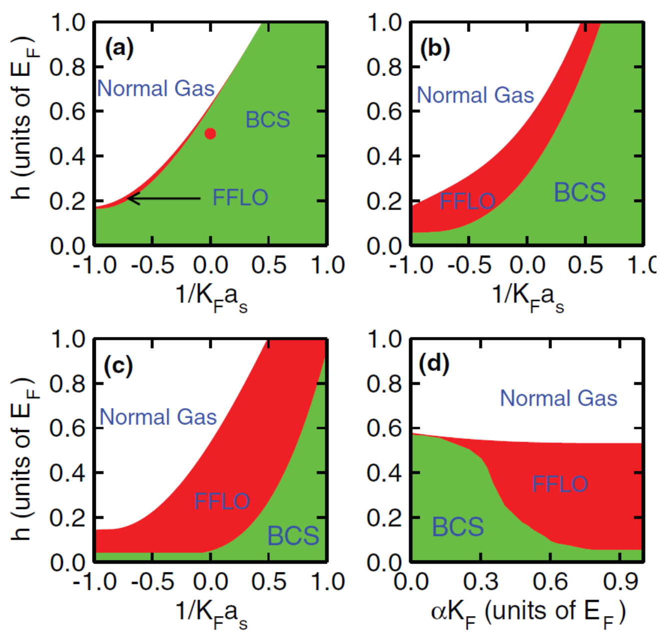


Figure Caption: BCS-BEC crossover phase diagrams in the presence of SO coupling and an in-plane Zeeman field. (a) Without SO coupling. The circle symbol represents the data from the quantum Monte Carlo calculation. (b) and (c) with SO coupling strength $\alpha K_F = 0.5E_F$ and $\alpha K_F = 1.0E_F$. (d) In the unitary regime.

Bose-Einstein Condensates in Spin-Orbit Coupled Optical Lattices: Flat Bands and Superfluidity,

Yongping Zhang, and **Chuanwei Zhang**

Phys. Rev. A 87, 023611 (2013). arxiv:1203.2389

Spin-orbit (SO) coupled superfluids in free space or harmonic traps have been extensively studied. However, the rich physics of SO coupled BEC in optical lattices has not been explored. In this project, we propose an experimentally feasible route for generating isolated flat bands using cold atoms in SO coupled weak optical lattices. Flat bands possess macroscopic level degeneracy because of their flat energy dispersion, and play a crucial role in many important physical phenomena. However, most previous lattice models for generating flat bands involve either high orbital bands or high order tunnelings, which are generally very challenging in experiments. We show that the combination of SO coupling, Zeeman field and optical lattice potential can yield isolated flat bands where topological properties may originate from the SO coupling.

Our proposed SO coupling mechanism, when generalized to 2D, may provide an experimentally feasible route for generating chiral flat bands and studying relevant fractional quantum Hall insulator physics. The stable superfluidity in the whole ground state band may lead to other interesting phenomena that have not been explored in regular optical lattices, such as dissipationless Bloch oscillation of BEC.

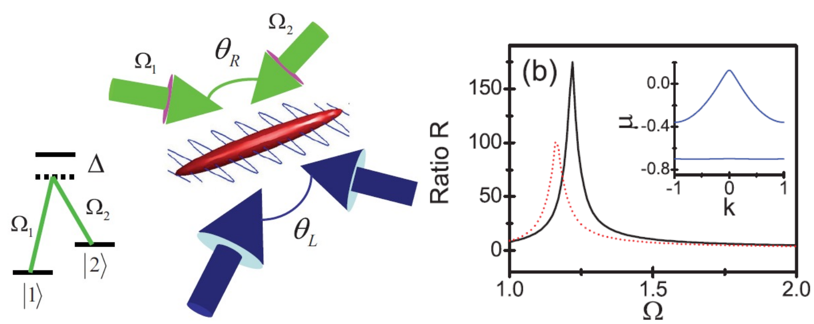
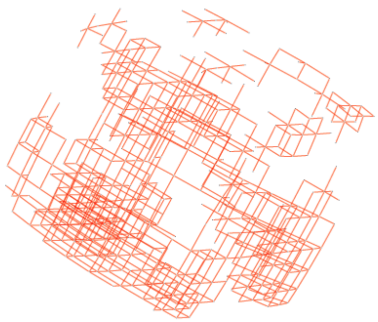


Figure Caption: (Left) The experimental scheme for generating flat band in spin-orbit coupled optical lattices. (Right) The flat band energy dispersion (inset) and the band flatness ratio R with increasing Raman coupling.

Percolation Enhanced Supersolids in the Extended Bose-Hubbard Model,
B.M. Kemburi and **V. W. Scarola**

Phys. Rev. B. **85**, 020501 (2012) arXiv:1110.2957

In this work we theoretically studied the stability of lattice supersolid states in the extended Bose-Hubbard model with bounded spatial disorder. We constructed a disorder mean field theory and compared with quantum Monte Carlo calculations. The supersolid survives weak disorder on the simple cubic lattice. We also found that increasing disorder strength can transform a lattice solid into a supersolid as it tends to percolate through the disorder landscape.



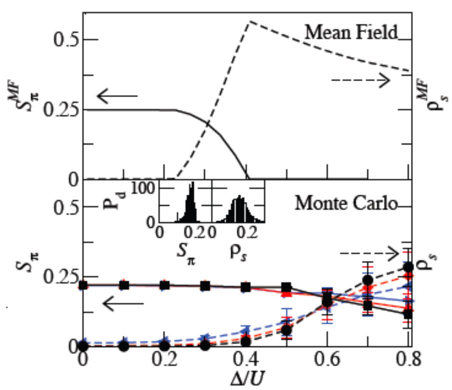


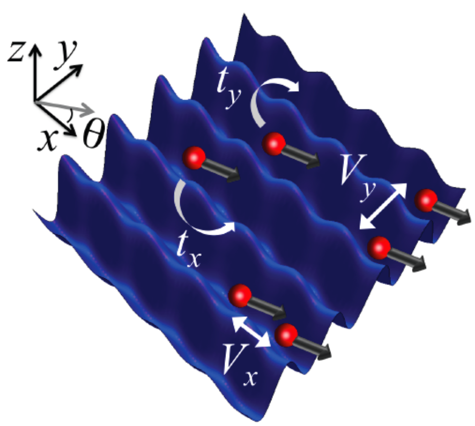
Figure Caption: (Left) Quantum Monte Carlo results for a single disorder configuration for the extended Bose-Hubbard model. We find solid order among all sites but we only plot a site if it has large density fluctuations. The supersolid is allowed to percolate from one edge to another only if local density fluctuations permit local superfluid order along enough connected bonds to cross the sample. (Right) The top and bottom panels plot order parameters to identify the superfluid using mean field theory and Quantum Monte Carlo. The left and right axis plot static structure factor and the superfluid density, respectively, for the disordered extended Bose-Hubbard model on a cubic lattice as a function of the disorder strength. The supersolid arises when both order parameters are non-zero.

Enhancing the thermal stability of entanglement between Majorana fermions with dipoles in optical lattices,

Fei Lin and **V.W. Scarola**

Phys. Rev. Lett. 111, 220401 (2013) arXiv:1210.0799

Pairing between spinless fermions can generate Majorana fermion excitations. Such excitations may exhibit intriguing properties arising from non-local entanglement, including anyonic braid statistics, teleportation, and enough stability to encode quantum information. But simple models indicate that non-local entanglement between Majorana fermions becomes unstable at non-zero temperatures. We addressed this issue by showing that anisotropic interactions between dipolar fermions in optical lattices can be used to significantly enhance thermal stability. We constructed a model of oriented dipolar fermions in a square optical lattice. We found that domains established by strong interactions exhibit enhanced entanglement between Majorana fermions over large distances and long times even at finite temperatures.



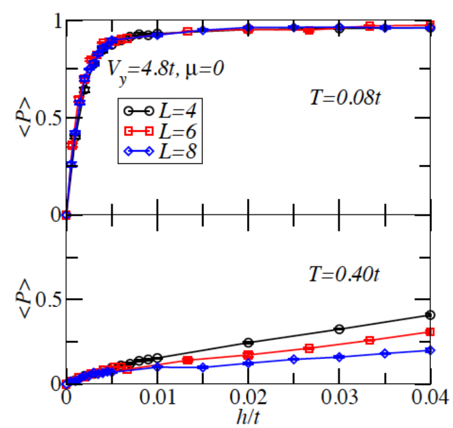


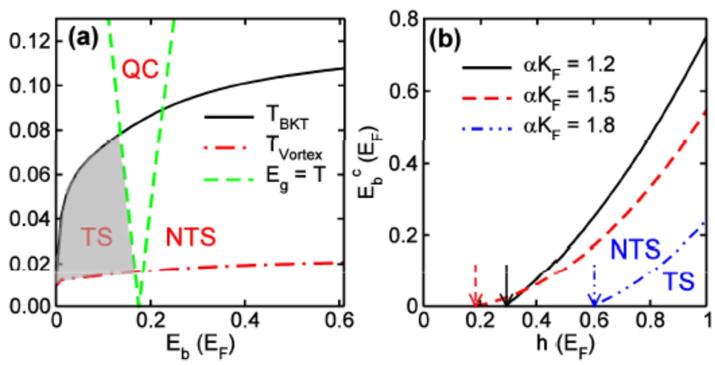
Figure Caption: (Left) Schematic of oriented fermionic dipoles in an optical lattice. Each x-row sets up a paired state (a Kitaev chain) with Majorana fermions at the end of each row. (Right) The fermion parity for Kitaev chains plotted as a function of a perturbing field for two different temperatures T. The high temperature plot shows the stability of Majorana fermion entanglement against thermal fluctuations.

Searching for Majorana Fermions in 2D Spin-orbit Coupled Fermi Superfluids at Finite Temperature,

Ming Gong, Gang Chen, Suotang Jia, **Chuanwei Zhang**

Phys. Rev. Lett. 109, 105302 (2012) arXiv:1201.2238 (**47 citations**)

Recent experimental breakthroughs in realizing spin-orbit (SO) coupling for cold atoms has spurred considerable interest in the physics of 2D SO coupled Fermi superfluids, especially topological Majorana fermions (MFs) which were predicted to exist at zero temperature. However, it is well known that long-range superfluid order is destroyed in 2D by the phase fluctuation at finite temperature and the relevant physics is the Berezinskii-Kosterlitz-Thouless transition. In this project, we examined finite temperature effects on SO coupled Fermi gases and showed that finite temperature is indeed necessary for the observation of MFs. MFs are topologically protected by a quasiparticle energy gap which was found to be much larger than the temperature. The restrictions to the parameter region for the observation of MFs have been obtained.



BCS-BEC Crossover and Topological Phase Transition in 3D Spin-Orbit Coupled Degenerate Fermi Gases,
M. Gong, S. Tewari, and **C. Zhang**,

Phys. Rev. Lett**.** 107, 195303 (2011). arXiv:1105.1796 (**125 citations**)

Ultra-cold degenerate Fermi gases (DFG) with population imbalance (equivalent to an effective Zeeman field) have sparked tremendous recent interest in both theory and experiment. The recent experimental realization of spin-orbit coupling (SOC) opens another new avenue for the study of DFG. We investigated, for the first time, the BCS-BEC crossover physics in DFG with both Zeeman field and SOC. The crossover physics is important because the s-wave superfluid, together with SOC and Zeeman field, may yield intriguing chiral p-wave physics with non-trivial statistical properties. For example, Majorana fermions and the associated non-Abelian statistics, the critical ingredients for performing TQC, may be observable only in the crossover region where the superfluid order parameter is large and thus robust against finite temperature effects. We showed that the superfluid order parameter destroyed by a large Zeeman field can be restored by SOC. At zero temperature, we found that there is a topological phase transition in such systems from a non-topological superfluid to a topological superfluid with increasing Zeeman fields or by tuning the s-wave scattering length. The two phases are separated by a critical point which itself is a gapless superfluid. We showed how the zero-temperature topological quantum phase transition can be probed at finite temperatures using cold atom photoemission spectroscopy which has already been realized in experiments.

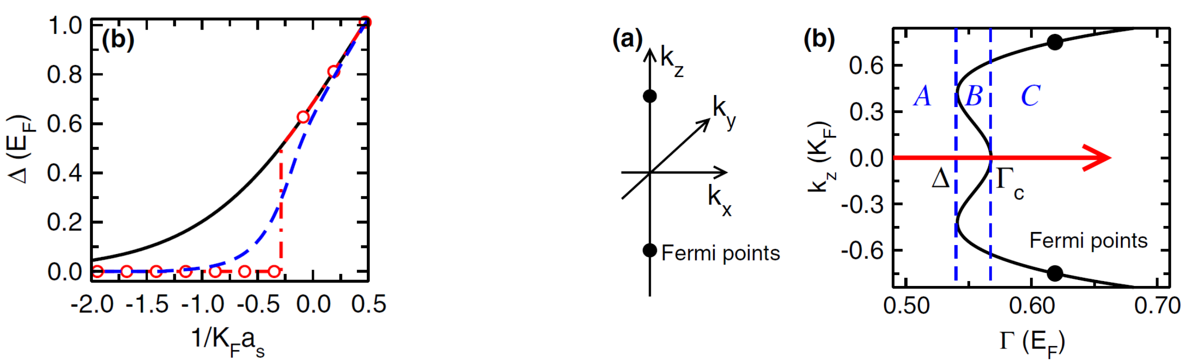


Figure Caption: (Left) Change of the order parameter in BCS-BEC crossover with spin-orbit coupling. (Right) The Weyl fermions in quasiparticle excitations and the corresponding topological phase transitions.